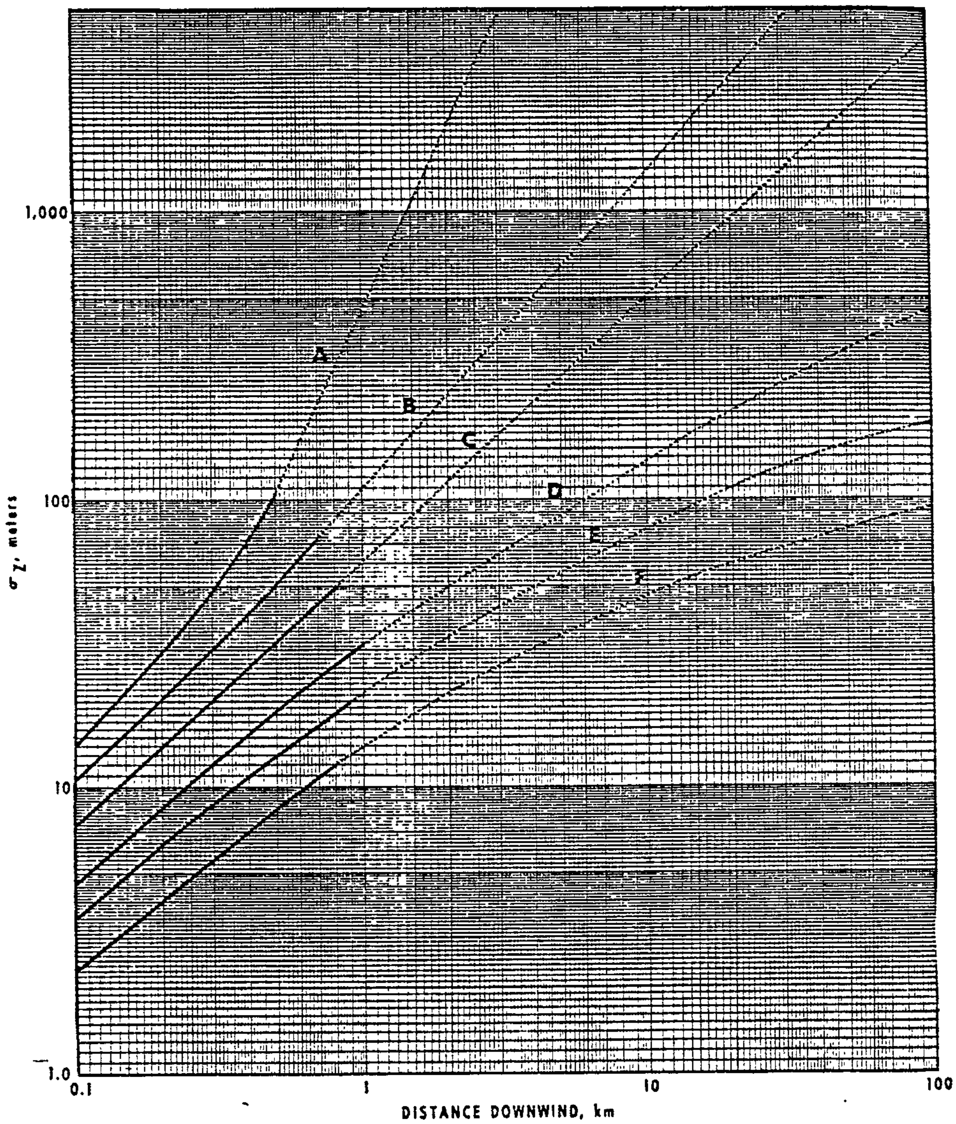
Table 23. Variation of σ_z With Downwind Distance from the Source



Source: D. B. Turner. 1964. "A Diffusion Model for an Urban Area," Journal of Applied Meteorology vol. 3, p. 91.

Table 63. Power Law Exponents and Coefficients for σ_y

Atmospheric Stability Class	Downwind Distance, meters x < 10,000		Downwind Distance, meters $x \geq 10,000$	
	c	d	c	d
A = 1	.495	.873	.606	.851
B = 2	.310	.897	.523	.840
C = 3	.197	.908	.285	.867
DD = 4	.122	.916	.193	.865
DN = 5	.122	.916	.193	.865
E = 6	.0934	.912	.141	.868
F = 7	.0625	.911	.0800	.884

Table 64. Power Law Exponents and Coefficients for σ_z

Atmospheric Stability Class	Downwind Distance, meters $100 < x \leq 500$		Downwind Distance, meters $500 < x \leq 5,000$		Downwind Distance, meters 5,000 < x	
	a	b	a	b	a	b
A = 1	.0383	1.2810	.0002539	2.0890	0.0002539	2.0890
B = 2	.1393	0.9467	.0493600	1.1140	0.0493600	1.1140
C = 3	.1120	0.9100	.1014000	0.9260	0.1154000	0.9109
DD = 4	.0856	0.8650	.2591000	0.6869	0.7368000	0.5642
DN = 5	.0818	0.8155	.2527000	0.6341	1.2970000	0.4421
E = 6	.1094	0.7657	.2452000	0.6358	0.9204000	0.4805
F = 7	.05645	0.8050	.1920000	0.6072	1.5050000	0.3662

NOTE: "DD" refers to Stability Class D-day
"DN" refers to Stability Class D-night

Source: Texas Air Control Board, User's Guide to the Texas Episode Model, (Austin, Texas, Texas Air Control Board, 1979) p.14.

APPENDIX E

THE COST OF RISK-BEARING AND ANXIETY

INTRODUCTION

We have argued that anxiety is an important component of the cost of bearing the risks associated with major environmental episode. But it is easier to state that proposition than to say what "anxiety" means. It seems clear that standard (Savage) expected utility theory does not capture such effects. At least two aspects of that theory support this assertion. First come those related to the remark, expressed intermittently in discussions of these theories, that gambles themselves can have utility. This cuts against the grain of standard (Savage (1971)) expected-utility theory, in which only outcomes have utilities. For descriptive accuracy, it may be necessary to attribute disutility to imposed (or involuntary) gambles. Normatively, an interesting question is: what axioms lead to representations attributing utilities (or disutilities) to gamblers. Second come those related to "time at which uncertainty resolves." In many discussions of these effects, we find the idea that disutility (in the case of "anxiety") or utility (in the case of "anticipation") attaches to waiting for information. To formalize these notions we need a framework in which the timing of the resolution of uncertainty matters.

Preliminary efforts at these two aspects are described below. But there may be other important related notions worth exploring. One place to look is in the more insightful literary treatments. For the record, here are two of the more intriguing digressions on "anxiety" in the current literature. In neither instance was there an effort at formalization.

The first is a paragraph of comment Thomas Schelling attached to an early draft of Zeckhauser (1974):

> Do you mean that a 'rational' individual could not be_subject to anxiety, or that he should ignore his own anxiety? If anxiety is uncomfortable or disabling as it usually is, then the rational person has be be concerned with it, just as he should be concerned with the pain and disablement of a broken bone. If you mean that a rational person should not be subject to anxiety, then we're back to the old question of where we draw the line between the 'rational individual' and

> the body he lives in. Am I a rational individual who resides in a nervous body, whose nervousness I cannot effectively control; or am I an irrational individual because the fear of death can keep me from sleeping, spoil my digestion, and make it hard for me to enjoy music?

The second is from Viscusi (1979):

> An important aspect of job hazards that cannot be readily incorporated in the analytic frameworks discussed thus far is the anxiety induced by hazardous jobs--that is, the effect on individual welfare of awaiting the outcome of a job hazard lottery. Interviews with workers reveal that the welfare of many workers is significantly affected by the expectation of unfavorable job effects. The instances of worker anxiety range from an air traffic controller's fear of getting ulcers to a B. F. Goodrich worker's worry about whether he has contracted liver cancer through exposure to polyvinyl chloride.
>
> A distinguishing economic feature of such phenomena is that the standard separability assumptions no longer hold. To analyze these influences, one can no longer assume that the future outcomes of job hazard lotteries do not impinge on a worker's present welfare. Consider the effect of anxiety on the dynamic programming methodology utilized in the preceding chapters. Traditional backward induction techniques optimize for the last period of the worker's choice problem, then optimize for the next-to-last period, assuming an optimal choice is made in the final period, and so on. Once anxiety is introduced, however, the optimal job hazard for the last period cannot be chosen in isolation, since the resulting anxiety from the choice has a backward influence on earlier welfare. This problem is especially great for career choices that represent long-term commitments, since the entire sequence of lotteries may affect one's anxiety. While a fully general analysis incorporating these temporal interdependencies tends to be unwieldy, it is somewhat easier to speak in general terms about how influences such as anxiety, anticipation, and suspense alter the earlier results.
>
> This effort is facilitated by applying and extending the analytic contribution of Zeckhauser (1974), who has reconciled these formerly aberrant cases with conventional von Neumann-Morgenstern utility

constructs. Much of the traditional difficulty with concepts such as anxiety arose from economists' failure to recognize that lotteries not resolved immediately are quite different entities from those resolved instantaneously. Thus, the cancer hazards posed by job A may be preferred to those posed by job B if the worker is informed of the health outcome immediately, whereas the preferences might be reversed if there were a five-year lag before the health effects would be known.

The models in this chapter develop the economic conceptualization of anxiety, devoting particular attention to its relationship to employment hazards. For example, how might one reformulate the worker's choice problem to analyze the influence of anxiety on compensating wage differentials for jobs with temporally remote hazards? Is there any medical evidence that anxiety induced by job hazards alters the probability of health and safety hazards, and what are the economic implications of such feedback effects?

The subsequent methodological arguments will focus on the negatively valued effects that I will refer to as anxiety. The analysis can be generalized with little difficulty to deal with positively valued temporal influences, such an anticipation, or influence whose desirability may be unclear, such as suspense.

Although the subsequent analysis will abstract from the diverse aspects of job risks, a multiplicity of job risk attributes actually contribute to the anxiety associated with a job. Why, for example, are the hazards facing a stock car racer or an astronaut considered exciting or perhaps glamorous, while the vibration-induced risks of spinal damage to a tractor driver viewed with less favor? Among the determinants of different worker attitudes toward anxiety effects are the perception of individual control over the risk, the desirability and familiarity of the possible outcomes, the probabilities attached to these outcomes, the imminence of the outcome of the job lottery, society's assessment of the job's importance, and the extent to which the hazard is viewed as being essential to the activity. Policy interventions in the job health and safety area seem to be motivated more by job risk attributes such as these rather than by more fundamental issues such as the severity of the outcomes involved or the extent of worker information about the hazard.

Appropriate consideration of the temporal resolution of lotteries provides an analytic motivation for job choices that otherwise would seem inconsistent with expected utility maximization. Suppose a worker must choose between two jobs that differ in the probability of injury, but otherwise are identical. Also assume that the worker prefers to remain uninjured when all other components of his utility function are unaltered. Static optimization would suggest that the worker always should pick the safer job. Yet, few analysts would deny that many workers may find some minimal risks enticing, if only to reduce life's monotony. Efforts to explain such behavior on the basis of worker risk loving (that is, willingness to accept some actuarially unfair monetary gambles) clearly are incorrect for the preferences I have delineated, since being healthy is assumed to be preferable to being injured. Even a risk lover will refuse to increase the probability of a less- preferred outcome if there is no additional compensation. If, however, one recognizes that job lotteries not resolved immediately entail anxiety or suspense effects in the time interval before the outcome is known, there need be no inconsistency with rational choice models.

A common feature of all of the temporal effects discussed above is that worker information is essential to any backward influence of lotteries resoved at some future time. The central role of information in producing an impact on individual welfare has been discussed extensively by Alfred Hitchcock in a series of interviews with Francois Truffaut (1967). Hitchcock observes: 'In the usual form of suspense it is indispensable that the public be made perfectly aware of all of the facts involved. Otherwise there is no suspense.' Hitchcock also provides examples that distinguish between suspense and surprise. If the audience is informed that a bomb may go off and kill several innocent people, there is suspense, whereas an explosion without any prior information involves only surprise.

These cinematic notions have direct parallels in the job risk situation and, more generally, in the economic analysis of anxiety effects. A coal miner who views the probability of contracting emphysema as being the same as that of getting hit by lightning will experience little anxiety. If, however, the miner observes signals of job characteristics, outcomes for other workers, or perhaps physical changes in himself,

> the probability of contracting lung disease may be revised upwards substantially, producing anxiety about his own health, and about the effect of a possible loss of income on himself and his family.
>
> It is this mingling of altruism and anxiety that no doubt is a principal contributor to the flourishing American life insurance industry. Somewhat curiously, economists have analyzed the desire for life insurance in terms of a bequest motive term appended to a conventional model maximizing the discounted sum of one's expected lifetime utility. This formulation would be reasonable if the value of purchasing life insurance were reaped principally at the time of one's death. However, it seems that the purchaser of life insurance reaps virtually all of the benefits in terms of anxiety reduction throughout his life, since the policy does not even become payable until after his demise. This observation would not be particularly surprising to insurance companies, whose advertising campaigns are directed almost exclusively at generating anxiety and guilt among uninsured husbands.

With these quotations in mind, we turn in the next section to a review of previous attempts at formalizing some of these notions of anxiety.

VALUING ANXIETY: SOME PREVIOUS EFFORTS

In this subsection we examine several attempts to go beyond the Savage framework. They can all be interpreted as efforts to capture two of the features of "anxiety" we have identified: preferences over the timing of the resolution of uncertainty, on one hand, and the attribution of a value to the gamble, on the other. In each case we offer a compressed statement of the results and some critical comments.

Zeckhauser (1974) and Viscusi (1979) write down the following expected utility function:

$$pu_H(a(p), x) + (1 - p)\, u_s(a(p), x) \qquad \text{(E.1)}$$

The notation is:

u_H, u_S	utility in health, injured states
p	probability of injury
$a(p)$	"anxiety" about injury
x	consumption

No representation-theoretic justification for this functional form is given. The heuristic argument is based upon intertemporal effects (delayed resolution of the job-injury lottery), but these are not modeled. Though the heuristic justification for this representation is specifically intertemporal, the easiest way in which to begin looking for a representation theorem may be with (the essentially atemporal) version of mixture theory produced by Herstein and Milnor (1953).

Viscusi argues for the superiority of this representation over the one implied by Savage's theory, but in his empirical work on job risks he does not use this approach, and thus never tests this theory against the Savage theory. But the two approaches give different "specifications" for the compensating wage differential problem. In principle, it should be possible to test them against one another.

Finally, note the strong "family resemblance" between the Zeckhauser-Viscusi representation and the one derived by Kahneman and Tversky (1979) in their version of prospect theory. If the functions u_H, u_S in (E.1) factorize into a product of functions of the two arguments, then Zeckhauscr-Viscusi becomes a special form of the Kahneman-Tversky form. In that latter case, there is no "decision weighting" of the probabilities.

Krantz-Luce Conditional Expected Utility Theory

These authors (and Kranz, et. al (1971)) suggest the narrowness of the class of functional forms allowed by the Savage (and related) axiomatizations. In particular, they propose one alternative functional form; the associated representation-theoretic question is left open. That form is:

$$u(f_A) = E[v(f_a) \mid A] + w(A) \tag{E.2}$$

where $u(f_A)$ ranks conditional acts, and v is the function on consequences. Equivalently,

$$u(f_A) = \sum_{s \in A} P(s \mid A)\ v(c(s)) + w(A) \tag{E.3}$$

where w is some function satisfying the usual additivity property (on disjoint elements A, B of the non-null subsets S)

$$w(A \cup B) = w(A)\ p(A \mid A \cup B) + w(B)\ p(B \mid A \cup B) \tag{E.4}$$

As these authors note, this is only one possibility. Another is

$$u(f_A) = \sum_{s \in A} P(s \mid A)\ v(c(s), w(s)) \tag{E.5}$$

In the specific case w(s) = P(s | A), this is close to the form proposed by Viscusi and Zeckhauser: for A = S, conditionals revert to unconditionals, and the above equation reduces to

$$u(f) = \sum_{s \in S} P(s)\ v(c(s),\ P(s \mid A)) \tag{E.6}$$

Thus the program suggested by these authors for exploring representation-theoretic bases for these functional forms is at the same time an approach to the respresentation problem for the Viscusi-Zeckhauser functional form.

Kreps-Porteus Temporal Lottery Theory

In contrast to the other work surveyed, the approach of Kreps and Porteus (1978) is explicitly intertemporal, so that we can try to identify (and value) specifically intertemporal features of "anxiety." But these authors invoke numerical probability distributions as primitives, a procedure subject to the objections of Krantz, et al. (1971).

Can the Kreps-Porteus results be obtained by methods free of these objections? Here is a plan for such an approach. It may given the Kreps-Porteus (1978) results--a representation theorem for preferences over lotteries that are intertemporal in some essential way. At the same time, numerical probabilities are not invoked as primitives, and the relationship to the basic proof techniques of measurement and representation theory is clearer.

First introduce the notion of "essentially intertemporal" lotteries. Begin with an example, perhaps the simplest nontrivial case, depicted in figure 24.

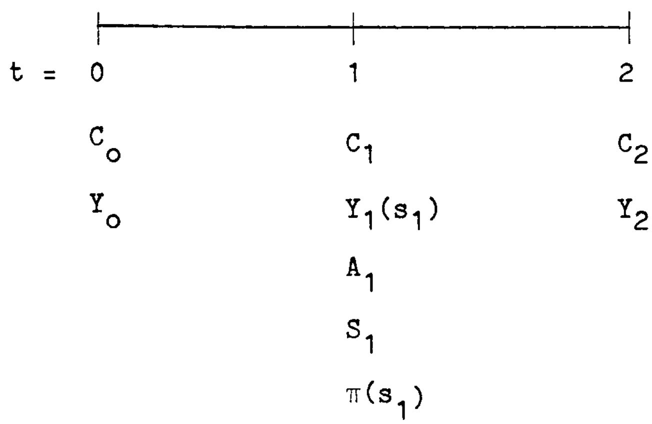


Figure 24. A Three-Period Temporal Lottery

At t = 0, 2, an individual receives income Y_o, Y_2 with certainty; at t = 1, income received, $Y_1(s_1^*)$, depends upon the realized state of nature

$s_1^* \in S_1$. Preferences over certain consumption streams, represented by a utility function $u(C_o, C_1, C_2)$, are taken as primitive.

In this example, the value of information (on the realized state of nature s_1^*) is the difference between the solutions to two maximization problems:

$$\text{(i)} \quad \max u(C_o, C_1, C_2)$$

$$\text{s.t.} \tag{E.7}$$

$$C_o + C_1 + C_2 \leq Y_o + Y_1(s_1^*) + Y_2$$

$$\text{(ii)} \quad \max u(C_o, C_1, C_2)$$

$$\text{s.t.}$$

$$C_o + \tilde{C}_1 + C_2 = Y_o + \min_{s_1 \in S_1} (Y_1(s_1)) + Y_2 \tag{E.8}$$

$$C_2(s_1^*) = \tilde{C}_2 + (Y_1(s_1^*) - \min_{s_1 \in S_1} (Y_1(s_1)))$$

The current-period consumption-good value of perfect information, I_o, can be expressed in terms of the solutions
(C_o', C_1', C_2'), (C_o'', C_1'', C_2'') to the two maximization problems as:

$$u(C_o' - I_o, C_1', C_2') = u(C_o'', C_1'', C_2'') \tag{E.9}$$

Finally, it may be the case that there is an expected-utility representation of preferences over uncertain income streams $(Y_o, Y_1(s_1), Y_2)$ induced by the (primitive) preferences over (certain) consumption streams. Thus, induced preferences and (uncertain) income streams are represented by:

$$v_o(Y_o, E(v_1(Y_1(s_1), Y_2))) \tag{E.10}$$

The expectation is computed with respect to a (subjective) probability distribution π_1 on S_1. Explicitly,

$$v_o(Y_o, \sum_{s_1 \in S_1} \pi_1(s_1)\, v_1(Y_1(s_1), Y_2)) \tag{E.11}$$

This form should be observationally distinguishable from the "payoff" vector form

$$\sum_{s_1 \in S_1} \pi_2(s_1)\, w(Y_o, Y_1(s_1), Y_2)$$

Proof should follow from separability arguments. In particular, both forms should be recoverable from observation, along the lines of Dybvig (1981).

The nested form of the representation is motivated by a guess at the way in which conjoint independence applies; that is further developed in the generalization of this example which follows. This example has a natural generalization, one which may point the way to a proof of a representation theorem. Begin by defining a three-period temporal lottery as a triple $\{(Y_o, S^{(o)}), (Y_1, S^{(1)}), (Y_2, S^{(2)})\}$. Each element is an ordered pair, consisting of a map and a subset of the states of nature. The map tells what realized income is, for any element in the associated subset, for that period. Note that income in each period necessarily resolves either during that period or earlier.

The subsets of the states of nature are, in general,

$$S^{(o)} = S_{(o)} \times S_{(1)} \times S_{(2)}$$

$$S^{(1)} = S_{(1)} \times S_{(2)} \qquad \text{(E.12)}$$

$$S^{(2)} = S_{(2)}$$

The associated maps

$$Y_o : S_{(o)} \to Y_o(s_o^*)$$

$$Y_1 : S_{(1)} \to Y_1(s_1^*) \qquad \text{(E.12)}$$

$$Y_2 : S_{(2)} \to Y_2(s_2^*)$$

are defined on the first-factor spaces. Now introduce three axioms. Consider preferences $\succsim$ defined on the space T of temporal lotteries.

(A1) Weak order
(A2) Pair dominance
(A3) Information valuing

Here are preliminary definitions:

Definition: The structure $\langle T, \succsim \rangle$ exhibits pair dominance iff for the temporal lotteries

$$T = \{(Y_o, S_{(o)}), Y_1, S_{(1)}), (Y_2, S_{(2)})\}$$
$$T' = \{(Y_o', S_{(o)}'), (Y_1', S_{(1)}'), (Y_2'), S_{(2)}')\} \tag{E.14}$$

the conditions

$$(Y_i', S_{(i)}') = (Y_i, S_{(i)}), \quad i = 0, 2$$

$$S_{(2)}' \equiv S_{(2)} \tag{E.15}$$

$$Y_1' (s_1') \geq Y_2(s_2'), \quad s_2' \in S_{(2)}'$$

imply

$$T' \succsim T$$

Definition: The structure $\langle T, \succsim \rangle$ is called information valuing if the conditions

$$S_i' \equiv S_i \quad i = 0, 1, 2$$

$$Y_i \mid S_i' = Y_i \quad i = 0, 1, 2 \tag{E.16}$$

where $Y_i \mid S_i'$ is the restriction of Y_i to S_i' imply

$$T' \succsim T$$

Then we want to prove a representation theorem along the following lines:

Conjecture: There exist real-valued utility functions $u_{(o)}$, $u_{(1)}$, and probability measures $\pi_{(o)}$, $\pi_{(1)}$ (defined on $S_{(o)}$, $S_{(1)}$, respectively) such that "expected utility"

$$\sum_{s_{(o)} \in S_{(o)}} \pi_{(o)}(s_{(o)}) u_{(o)}$$
$$(Y_o(s_{(o)}), \sum_{s_{(1)} \in S_{(1)}} \pi_1 (s_{(1)}) \, u_{(1)}(Y_1(s_{(1)}, Y_2(s_{(1)}))$$

"represents" the structure $\langle T, \succsim \rangle$. That is,

$$T_1 \succsim T_2 \quad \text{iff} \quad E_u(T_1) \geq E_u(T_2)$$

Here is an idea for a proof. The axioms (A1) through (A3), perhaps supplemented with others, imply a conjoint (but not additive) independence property between the first, and subsequent, factors. Then apply the usual construction. Kreps and Porteus (1978) carry through something like this program a la von Neumann-Morgenstern. Again, this is objectionable because numerical probabilities are introduced as primitives.

Finally, note that this kind of representation theorem can be used to value imposed intertemporal risks, and will (in general) distinguish between uncertainties resolving at different times. Thus it accomodates at least this aspect of "anxiety."

Kahneman and Tversky's Prospect Theory

In several respects, the Kahneman-Tversky (1979) theory is similar to that put forward, in a much less systematic and rigorous way, by Zeckhauser and Viscusi. In particular, both draw their inspiration from arguments about sequential and intertemporal effects. But neither set of authors works from a theory of the individual risk valuation to a full-fledged representation theory. In the case of Zeckhauser and Viscusi, the functional form is simply written down, with the "anxiety" function ad hoc. In the case of Kahneman and Tversky, the beginnings of a systematic theory--assembled in the first half of the paper--are not really the basis for the formal (prospect valuation) theory of the second half of the paper. In that second half, attention is restricted to "simple," or atemporal prospects. The authors suggest (without proof or the presentation of an example) that the apparatus of the first half of the paper can, in fact, lead to choice phenomena (like the violation of transitivity) that are in fact inconsistent with the theory of the second half of the paper (value functions always generate weak orders).

But the Kahneman-Tversky paper is important because it calls attention to several phenomena--such as the decision-weighting of low probabilities--that must be significant for individual valuations of major environmental episodes.

Some Further Approaches Worth Exploring

Perhaps the most important among these is due to John Chipman (197), whose work on non-Archimedean theory has roots in earlier work on safety-first approaches to behavior under uncertainty. The latter has obvious relevance to the major environmental episodes case: specifically, it emphasizes ways of avoiding extreme losses. It also raises some disturbing questions about the general strategy around which much experimental work has been built: selective testing of the axioms.

Chipman has chosen to explore the consequences of dropping an axiom that is a staple of representation-theoretic proofs--and is particularly lacking in behavioral content (though not, as Chipman shows, in behavioral implications). The Archimedean axiom in effect says that all choice objects are "comparable" in a particular sense not to be confused with completeness (or connectedness) of the weak order from which almost all theories of rational choice begin. Chipman works in a variant of the Herstein-Milnor (1953) mixture-space theory, perhaps because it is easier than the (in principle superior) approaches which do not introduce probabilities as primitives; his approach can be extended in the latter direction. The results are, in a sense, not surprising, although it should be possible to make the proof more transparent. Dispensing with the kind of "comparability" provided by the Archimedean axiom radically alters the extent to which the primitive weak order is "reduced." In conventional expected utility theory, the "reduction" is to one dimension: expected utility is a real-valued function defined on all prospects.

In Chipman's non-Archimedean case, an n-1 dimensional expected utility vector-valued function is defined over a set of n prospects, and the primitive preference ordering of those prospects is represented by a lexicographic order of the expected utility vectors. The implications for valuation are intriguing; under some circumstances, individuals acting in accord with Chipman's representation theory will not trade some dimensions against others at any finite shadow price. But if the data on such individual's revealed choices (under feasibility constraints) are misinterpreted as having arisen from conventional expected-utility maximizing behavior, the possibility of an imputation of downward-biased shadow prices (of lexicographically dominant components) arises. Approaches similar to Chipman's are cited by him; this strand in the literature is called "safety first," and associated with the names and work of Roy (1952) and Telser (1955).

Finally, take note of one more general implication of Chipman's results. For valuation, what matters is the representation chosen; while axiomatizations of representations provide some insight into their inherent plausibility, the valuation estimate finally stands or falls on the representation. Much experimental work has emphasized the axioms, and not the representation. A more efficient research strategy might be: arrange experiments (or econometric exercises) which set up confrontation between candidate representations.

"ANXIETY": SOME REINTERPRETATIONS

We begin by bringing together some of the very different notions of "anxiety" implicit in the vague, general notions we all carry with us. In the previous sections, we have identified anxiety as: probability revision, state dependence, sequentiality, and belief-preference interdependence.

(PR) Anxiety as probability revision: the underlying ideal is that individuals are skeptical of the independence of even "genuinely" independent events. When rare, damaging events occur, they revise subjective probabilities upwards; subsequently, barring repetitions, those same probabilities are reviewed downwards by the same moving-average model. Since subjective probabilities are the relevant ones for risk valuation, those revised probabilities are what matter for estimates of the cost of risk bearing.

(SD) Anxiety as state dependence: choosing some gambles, or being subjected to others, effectively changes the individual's utility function, so that subsequent lotteries are evaluated differently.

(SEQ) Anxiety as sequentiality: the valuation of intertemporal lotteries can depend on the timing of the resolution of uncertainty. This can happen in two distinct ways, either or both of which may be present in particular cases. The first is a pure "rebudgeting," or intertemporal reallocation effect: earlier knowledge is valuable, because it makes better intertemporal allocations attainable. The second we call a "pure knowledge" effect: utility depends upon knowing something will happen in the future, independently of being able to do anything about it. This latter case is indistinguisable from what we have called "state dependence."

(BPI) Anxiety as belief-preference interdependence: here utility depends directly upon probabilities; the characteristic independence results of expected utility theory break down.

In this section, we explore the two interpretations of the notion of anxiety, and we look at the implications for the valuation of risk.

<u>Anxiety As "Inappropriate Probability Revision": The Limits of Normative Theory</u>

Our point of departure is a review of the Bayesian approach to probablity revision, an approach that is essentially normative. Suppose that an individual is subject to some low-probability hazard associated with some environmental episode, and further suppose that his prior distribution on the episode probability is "about right." Introduce the following notation and variables:

P	Episode probability
$f_o(p)$	Prior distribution on p
$f_\beta(p \mid r,s)$	Beta distribution with parameters r,s
$f_1(p)$	Posterior distribution on p

Recall some elementary properties of the beta distribution:

(B1) For all r,s $f_\beta(p \mid r,s)$ is nonzero only on the (closed) interval [0,1].

(B2) The mean $E(p \mid r,s)$ and variance (about the mean) $V(p \mid r,s)$ of the beta distribution are given by

$$E(p \mid r,s) = \frac{r}{r + s}$$

$$V(p \mid r,s) = \frac{rs}{(r + s)^2(r + s + 1)} \tag{E.17}$$

(B3) For a beta-distribution prior $f_0(p) = f_\beta(p \mid r,s)$ and an underlying binomial probability model, if s_1 additional observations yield r_1 "successes" and $s_1 - r_1$ "failures," then the posterior distribution is also a beta distribution

$$f_1(p) = f_\beta(p \mid r',s') \tag{E.18}$$

with

$$r' = r + r_1$$
$$s' = s + s_1 \tag{E.19}$$

This is perhaps the most widely used and influential model of subjective probability revision: let us see what it implies for the episode cases. There, we suppose that the individual begins with some prior distribution $f_o(p)$ on the probability of an episode. that probability can, and will, be revised in the light of subsequent experience. But the model severely limits that revision process. If, for example, the episode genuinely is a low probability episode, and if the individual's prior distribution is "about right," then that distribution will not be seriously modified by experience of an episode. The reason is easy to see: if the mean $E(p \mid r,s)$ is small and the prior distribution tight, then r is small relative to s, and the change from r,s to r',s' in the revision will not significantly change the mean. Thus, the beta-binomial model cannot describe the fillowing sequence: revision of an "accurate" prior into a posterior which overestimates episode proabilities, and subsequent downward revision of that overestimate toward the correct estimate. Because that latter sequence seems to be an accourate description of what many individuals do after a rare event, let us look a little deeper into why the beta-binomial model, an attractive normative model, rules out such sequences. Following that, we will provide an independent description of those sequences.

Can it happen that an individual, acting in accord with the Bayesian prescription for probability revision, revises in the above "nonmonotonic" fashion? We suspect that the answer is no, at least so long as the model is limited to sufficient statistics and conjugate distributions, related notions central to many applications of the Bayesian calculus. But an approach to a rigorous argument first requires that we provide a rigorous definition of the notion of monotonicity for a sequence of distributions. This problem, and some related, ones that arise quite anturally along the way, have not to my knowledge been given a definitive treatment. What follows is therefore both exploratory and preliminary.

Here is the notion we wish to make rigorous. A Baysian begins with a prior distribution $f_o(p)$ on a proportion, a number known to lie in the (closed) interval [0,1]. At regular intervals he is handed additional sample information free of charge. Now ask: what can be said about the (or a) rate of convergence to an ultimate, posterior distribution $f_1(p)$?

Suppose that the additional inormation comes in the form of the outcomes $[e_1,e_2,\ldots,e_n]$ of "experiments," and that those "experiments" are drawings on independent, identically-distributed random variables. Then after the information $[e_1,e_2,\ldots,e_n]$ is in hand, the prior distribution has been revised to $f_n(p \mid [e_1,e_2,\ldots,e_n])$, where

$$f_n(p \mid [e_1,e_2,\ldots,e_n]) = \frac{\ell([e_1,e_2,\ldots,e_n] \mid p)}{C([e_1,e_2,\ldots,e_n])} f_o(p) \qquad \text{(E.20)}$$

Here we have introduced the following notation:

$\ell([e_1,e_2,\ldots,e_n] \mid p)$	The likelihood function of the data
$C([e_1,e_2,\ldots,e_n] \mid p)$	A normalization constant insuring that f_n is a probability distribution function
$h(e_1,e_2,\ldots,e_n)$	Marginal prior distribution on outcomes of experiments

Given that explicit form for f_n, we can try to write down a norm on the distirbutions generated by successive "experiments," and the requise, subsequent Bayesian revisions. Only one further problem remains: the "correct" averaging over the sequence $[e_1,e_2,\ldots,e_n]$ generated by the observations. Remember that these are random sequences, since they are realizations of the random vectors $[E_1,E_2,\ldots,E_n]$. Thus, a proper norm concept on the sequence of posterior distributions f_n must average over both the functional argument p, in the usual way, and over the random variable, in a way that follows from elementary probability distribution theory.

Here is a candidate, simply written down: we use the prior distribution h on the random variable E representing the experiment, and then compute

$$|f_n - f_m| = \sum_{\substack{e_i=0,1\\ i=0}}^{k} h(e_1,e_2,\ldots e_n) \int_0^1 dp \; |f_n(p \mid [e_1,e_2,\ldots e_n]) - f_m(p \mid [e_1,e_2,\ldots e_n])| \tag{E.21}$$

This proposed norm clearly is a norm; the defining properties are easy to check. It may, nevertheless, be deficient in one important respect: the norm notion has nothing to do with the decision-relevant loss measure, and concerns itself only with the actual sequence of probability distributions. But for descriptive accuracy, as opposed to the usual normative decision-theoretic requirements, that is the sequence that is of interest. And in terms of that norm, we can at last give an unambiguous statement of what we suspect is the reason for the descriptive inadequacy of the beta-binomial Bayesian model (and all other Bayesian models based upon sufficient statistics and conjugate distributions).

Conjecture: When there are sufficient statistics, and when experimental information is generated by observations on independent, identically-distributed variables, then the corresponding sequence of posterior distributions f_n always converges monotonically in the norm defined by (E.21).

Specifically, note that the independence assumption guarantees

$$h(e_1,e_2,\ldots,e_n) = \prod_{i=1}^{n} h(e_i) \tag{E.22}$$

and that the sufficiency assumption implies that

$$f_n(p \mid [e_1,e_2,\ldots,e_n]) = g_n(p \mid z(e_1,e_2,\ldots,e_n)) \tag{E.23}$$

for some sufficient statistic z and some probability distribution function g_n. Thus, the norm written in (E.21) reduces to the form

$$|f_n - f_m| = \sum_{\substack{e_i=0,1\\ i=0}}^{n} \prod_{i=1}^{n} h(e_i) \int_0^1 dp \; |f_n(p \mid z(e_1,e_2,\ldots e_n)) - f_m(p \mid z(e_1,e_2,\ldots e_m))|, \quad m < n \tag{E.24}$$

which must be the starting point for proofs of the above conjecture.

The Proposed Norm: An Example

Because the proposed norm sometimes looks counterintuitive, an example may be convincing evidence that the averaging suggested is, in fact, the correct averaging. In the example below, adapted from Ferguson (1967), we are actually able to go further and produce a norm based upon the relevant loss function. Begin by introducing the notation and variables

S	States of nature
A	Actions
L	Loss function
d	Decision rule
X	Experimental random variable

Next recall the definition of a Bayes' decision rule.

Definition: A Bayes decision rule (BDR) is a map from observations to action, $d(x) \in A$, which minimizes posterior conditional (on observations) loss

$$\int L(s,d(x))dF(s \mid x) \tag{E.25}$$

For the example, take

$$\begin{aligned} S &= A = [0,+\infty] \\ L(s,a) &= c(s-a)^2 \end{aligned} \tag{E.26}$$

with c a positive constant. Then suppose that, in the experiment, we observe a random variable X which is uniformly distributed on the interval $[o,s]$: that is, X has the distribution $U[o,s]$ given by:

$$f(x \mid s) = \begin{cases} 1/s & 0 < x < s \\ 0 & \text{otherwise} \end{cases} \tag{E.27}$$

Then we want a BDR relative to the prior distribution $f_o(s)$ given by

$$f_1(s) = \begin{cases} sc^{-s} & s > 0 \\ 0 & s \leq 0 \end{cases} \qquad \text{(E.28)}$$

But the joint density is

$$h(x,s) = f_1(s)f(x \mid s) \qquad \text{(E.29)}$$

Thus the marginal prior distribution of X is

$$h(s) = \int dsh(x,s) = \begin{cases} e^{-x} & x > 0 \\ 0 & x \leq 0 \end{cases} \qquad \text{(E.30)}$$

and the posterior distribution of s, conditional on X = s, is

$$h(s \mid x) = \frac{h(x,s)}{h(x)} = \begin{cases} e^{x-s} & s > x \\ 0 & s < x \end{cases} \qquad \text{(E.31)}$$

In terms of these distributions, we can write down the posterior expected loss, conditional on X = x: it is

$$E\{L(s,a) \mid X = x\} = ce^{x} \int_{x}^{+\infty} (s-a)^2 e^{-s} ds \qquad \text{(E.32)}$$

Thus, to find d(x), the BDR, we must solve the equation

$$D_a E\{L(s,a) \mid X = x\} = 0 \qquad \text{(E.33)}$$

But in this simple setting, that solution is relatively easy: we get

$$d(x) = x + 1 \qquad \text{(E.34)}$$

Finally, we can exhibit the prior (expected) posterior loss, the analog, in this example, of the averaging performed in our construction of the norm (E.21): we get

$$\int_0^\infty dxh(x)E\{L(s,d(x)) \mid X = x\} \tag{E.35}$$

This is the relevant measure for comparing Bayes Decision Rules with other decision rules.

Anxiety As Probability Revision: A Descriptive Theory and Its Implications for Valuation

We have explained the inadequacy, for our purposes, of the standard normatively-oriented Bayesian models of probability revision. Our purpose in this section is to give a preliminary account of an alternative theory, one better suited to the task of estimating individual valuations of episode risks. The reader is again warned that much of what follows is speculative, but we have tried to be explicit about where the speculation comes in.

Under the standard Bayesian model of probability revision, a major episode and its consequences would run something like this. All individual would already "come equipped" with a prior distribution on the probability of a release into the environment (we use releases and episode occurance interchangeably, on a moment's reflection it will be clear that the two are distinct, and why). When the episode occurs, those individuals apply the Bayesian calculus to arrive at a posterior distribution. The distribution relevant to ex ante valuation exercises is the prior distribution; the distribution relevant to ex post valuation exercises is the posterior distribution.

But accepting the Bayes model severely restricts the kinds of revision that can be described. Since a single observation will not significantly affect any prior beliefs held with some degree of confidence, there will be no great difference between pre and post-episode beliefs.

This seems to be so far from what individuals actually do that we have tried to sketch a very different model of individual reaction to the occurence of any episode. That model begins with a few assumptions, but then accepts portions of the Bayes model as descriptive of individual behavior beliefs after an episode. It isolates a few parameters as central to the revision process, and points the ways of estimating those parameters.

We begin by stating:

Assumption: Before an episode of a kind not previously experienced, individuals have no sharply defined beliefs about the probability of such an episode. In the wake of an episode, they acquire such beliefs, but by assimilating the episode probability distribution to some other, more familiar, probability distribution. Characteristically, the mean of the resulting episode distribution is considerably higher than the "true mean."

Assumption: After an episode, as experience accumulates and there are no further episodes, individuals in effect apply the Bayesian calculus, revising successive posterior distributions downward toward the "true" episode distribution.

Thus there are two critical parameters for individual episode valuation under these assumptions: the parameters of the "more familiar" probability distribution to which the newly registered episode distribution is assimiliated, and the time period taken as relevant for concluding that there has been no observation of a second episode.

So much for a literary description of what we propose: let us give a more rigorous account. Begin with two figures illustrating what individuals may do following an episode. In figure 25, the actual post-episode (or posterior) distribution is the distribution that would result from "single-event" revision of the uniform distribution. The latter represents "complete ignorance"; the relatively large mean of the distribution $f_1(p)$ suggests the effect we have described. Of course, after many periods, that mean is described downwards, as observations of "no episode" are used to revise the distribution $f_1(p)$. Given some large enough number of observations, the resulting revisions will in fact produce the "true," or large sample distribution $f_\infty(p)$, with a mean that is in fact quite small. But in the interim, the individual will hold beliefs about the probability of subsequent episodes that are substantially higher than "the truth." An because the cost of risk-bearing depends only upon the individual's subjective beliefs, those costs will be higher than the costs computed at "actuarial" values of the episode probability.

Figure 26 illustrates some of the same ideas by presenting another pattern of individual response to an episode. There, the individual holds a set of prior beliefs which attribute a small probability (low mean) to an episode, but with very little confidence (large variance). Subsequent to the episode, however, those beliefs are shifted rapidly upwards, to $f_1(p)$, a distribution with a much higher mean and a much smaller variance. Then, over time, as no further episodes follow, that distribution is revised downwards to the true, "large sample" distribution $f_\infty(p)$. This sequence is meant to illustrate what was called, in the text, a "nonmonotonic" revision of probabilities, one which seems plausible but is ruled out when the existence of a sufficient statistic guarantees the existence of conjugate distributions.

Now let us turn to the implications of these arguments for individual valuation of the cost of bearing the risk of an episode. Suppose that time

Figure 25. How Individuals "Actually" Revise Probabilities

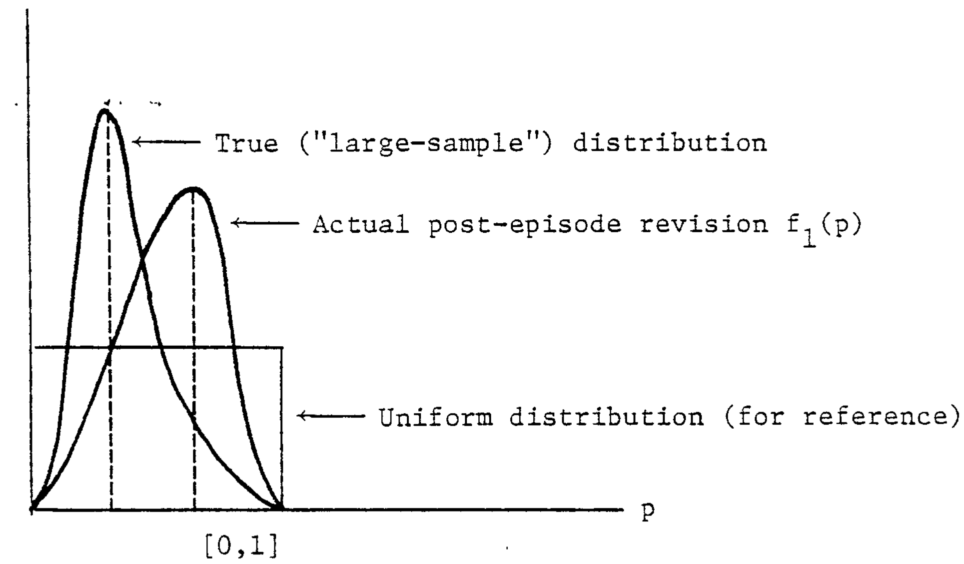
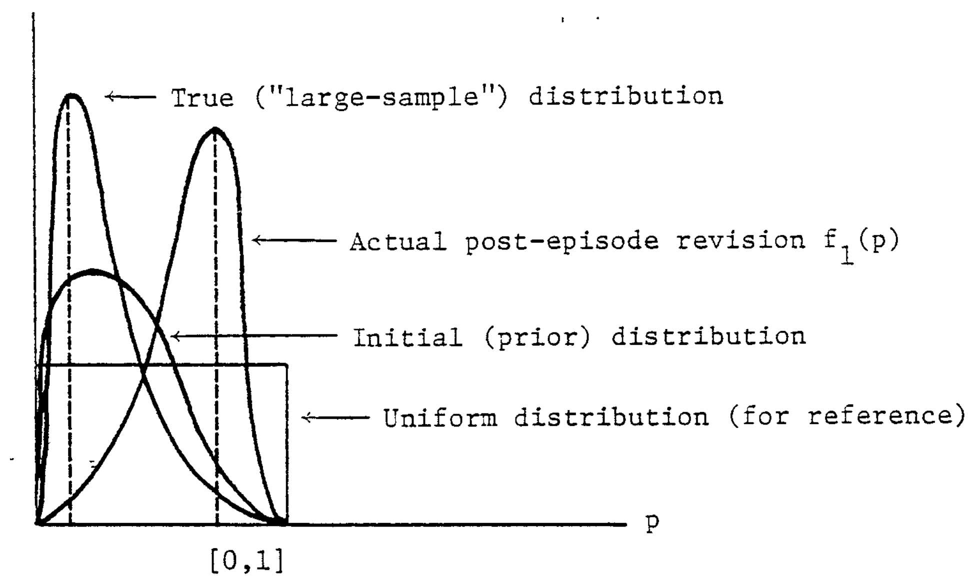


Figure 26. Another Possibility



is divided into discrete units called "days," and that an episode occurs on day 1. Further, suppose that immediately after the episode, the individual adopts the beta distribution $f(p \mid 1,2)$, which is just the uniform distribution $U[0,1]$ on the unit interval, as an appropriate representation of his beliefs. As time passes, that distribution is revised: for every day that passes without an episode, the second parameter of the current beat distribution is incremented by one. After n "days" without a repetition of the original episode, the individual holds beliefs $f(p \mid 1,2+n)$ about the probability of an episode occurring. Now we propose the following method for valuing individual episode risks.

Method: the relevant intertemporal lottery for valuing individual risks is the lottery represented by the sequence of risks

$$\{f_{\beta}(p \mid 1,2+n)\}_{n=1}^{d} \tag{E.36}$$

where d is some cut-off (representing, for example, the maximum number of days in a lifetime).

Here is an illustrative example. Suppose we then value incremental (daily) mortality risk at λ_D;

$$r_D = \lambda_D \sum_{n=1}^{d} \frac{1}{3+n} \tag{E.37}$$

Since

$$\frac{r_D}{\lambda_D} + \frac{3}{2} = \sum_{n=1}^{d} \frac{1}{n} \tag{E.38}$$

we need the right-hand side sum s(d). But we have the upper bound

$$\sum_{n=1}^{d} \frac{1}{n} \leq \log d \tag{E.39}$$

For the particular values

$$\begin{aligned} d &= (365)(10) = 3650.0 \\ \lambda_D &= \frac{10^{+6}}{365} = 0.3 \times 10^{4} \end{aligned} \tag{E.40}$$

we obtain

$$r_D = \lambda_D(\log 3650 - \tfrac{3}{2}) = (\lambda_D)(6.70) = 0.2 \times 10^5 \qquad \text{(E.41)}$$

Thus the critical issue is the "relaxation period." If we interpret the unit of observation as the year then, with y = 15 years,

$$r_A = \lambda_A \sum_{n=0}^{y} \frac{1}{3 + n} \qquad \text{(E.42)}$$

Finally

$$r_A = \lambda_A(\log y - \tfrac{3}{2}) = 1.21 \times 10^6 \qquad \text{(E.43)}$$

Compare (E.41) and (E.43): the sensitivity of the resulting figures (dollar values of the cost of risk bearing) is obvious. Let us conclude this exposition by summarizing what we must know to make use of this method:

Requirements for Implementation of Methods: we need to know

(IP) What initial probability (r and q in $f_\beta(p \mid r,q)$) do you assign after observing an "episode?"

(RP) What is your "relaxation period" for using post-episode experience to modify that initial estimate?

(PE) Is it true that pre-episode, you assigned "no damage" (didn't think about) this class of episode?

Anxiety As Sequentiality and Latency

Here is a very simple model allowing explicit calculation of an "anxiety-latency related" cost of risk bearing. Introduce notation and variables as follows:

u	Utility "per period"
T	Lifetime
c_t	Consumption in period t
h_t	Health status in period t (discrete: 1 = well, 0 = sick)

$y(h_t)$	Labor income in period t
e_1	"Exposures" (to "carcinogen") in first period
$\pi_t(e_1)$	Probability of "transition" (sick to well) in period t

Then under *no episode" (and therefore no exposure) assumptions, individuals solve

$$\text{Problem (NEX): } \max \sum_{t=1}^{T} u(c_t,\ 1)$$
$$\text{s.t. } \sum_{t=1}^{T} c_t \leq \sum_{t=1}^{T} y(1) \tag{E.44}$$

But under "episode" (and therefore exposure) assumptions, individuals solve

$$\text{Problem (EX): } \max \sum_{t=1}^{T} \pi(h_t,\ e_1)u(c_t,\ h_t)$$
$$\text{s.t. } \sum_{t=1}^{T} c_t \leq \min_{\{h_t\}_{t=1}^{T}} \sum_{t=1}^{T} y(h_t)$$

Regarding the form of the constraint, note that

(1) Nonexistence of relevant contingent claims markets forces use of min in rhs constraint

(2) Minimization is over feasible sequences $\{h_t\}_{t=1}^{T}$. But I will assume below (for simple preliminary calculations) that only two sequences are feasible. The two are depicted in figure 27.

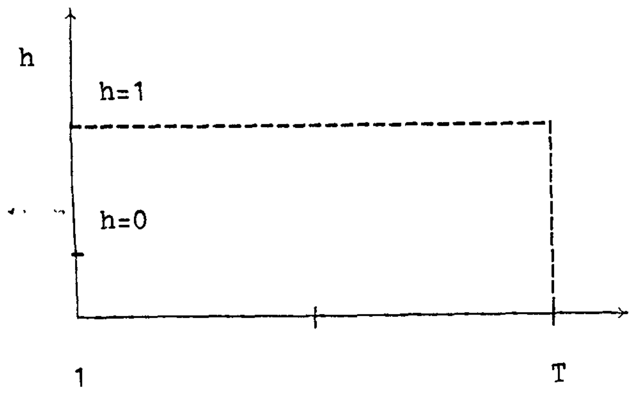
Then the cost of risk-bearing v is determined from

$$\sum_{t=1}^{T} u(c_t^*,1) = \pi_1(h_1,e_1)u(c_1^+ + v,1) + \sum_{t=2}^{T} \pi_t(h_t,e_1)u(c_t^+,h_t) \tag{E.46}$$

where we have introduced

c_t^*	Optimizing values from problem NEX
c_t^+	Optimizing values from problem EX

Sequence S1



Sequence S2

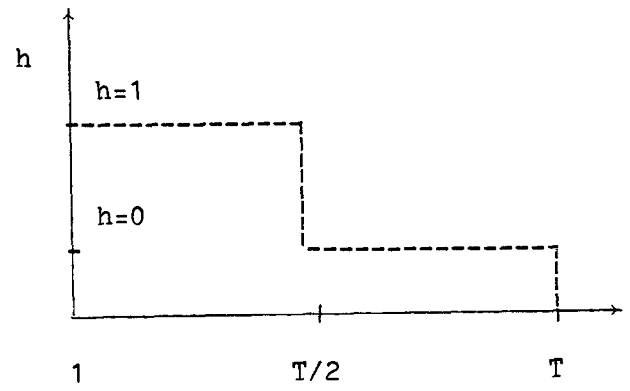


Figure 27. Feasible Health-Status Sequences

For preliminary work, we will take $\pi_t(e_1)$ of the form:

$$\pi_t(h_t, e_1) = r(e_1)\gamma_t(h_t) \tag{E.47}$$

where

$r(e_1)$	Dose-response factor
γ_t	"Standard" risk profile

For example, γ_t might be taken as depicted in figure 28 below.

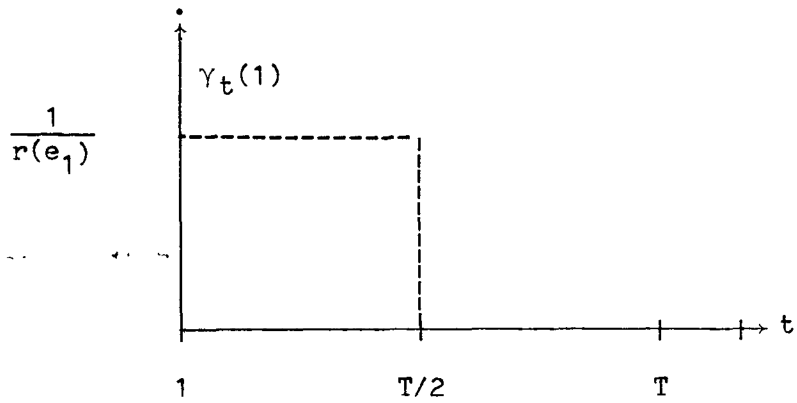


Figure 28. A Standard Risk Profile

$$\text{Note that } \pi_t(1,e_1) + \pi_t(0,e_1) = 1, \quad t = 1, \ldots, T \tag{E.48}$$

Thus, an implementation of the above model can give a value for v.

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